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CONF-871110--11

LA-UR -87-3677

LA-UR--87-3677

DE88 003182

TITLE CURRENT SEGMENTED GAMMA-RAY SCANNER TECHNOLOGY

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SUBMITTED TO American Nuclear Society
Third International Conference on
Facility Operations - Safeguards Interface
San Diego, California
November 29-December 4, 1987
(FULL PAPER)

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FORM NO. 836 R4
ST. NO. 2629 5/81

CURRENT SEGMENTED GAMMA-RAY SCANNER TECHNOLOGY

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ABSTRACT

A new generation of segmented gamma-ray scanners has been developed at Los Alamos for scrap and waste measurements at the Savannah River Plant and the Los Alamos Plutonium Facility. The new designs are highly automated and exhibit special features such as good segmentation and thorough shielding to improve performance.

I. INTRODUCTION

The assay of scrap and waste in the nuclear fuel cycle continues to be an important component in nuclear material accountability. The segmented gamma-ray scanner (SGS) is an important measurement tool for the class of low-density materials. Segmentation, rotation, and transmission measurement at each segment provide assay capability for items having some degree of heterogeneity within the volume of their containers. The SGS technique results in negligible bias for samples containing fine particles of nuclear material dispersed throughout the matrix of waste materials.

Historically, SGS measurements have been plagued with background interferences from nearby radiation sources because of inadequate shielding of the detector. They have also suffered from less than ideal segmentation when the distance between the detector collimator and the sample is too large. Figure 1 shows a schematic representation for an SGS, where the detector is properly shielded and the collimator-to-sample view angles are depicted. It is obvious from the figure that a collimator with a large aspect ratio of horizontal depth to vertical slit-height and with proximity to the sample yields good segmentation, that is, vertical view angles of minimal vertical extent.

Because the correction factor for attenuation is dependent upon the relative geometry among the detector crystal, the collimator slit, and the sample, errors have also been made by calibrating with containers much smaller than the usual assay containers but not using independent correction factors for the two differing geometries. To address such issues for specific plant requirements, the Los Alamos Safeguards Assay Group designs, builds, tests, installs, and evaluates prototype nondestructive assay instruments for the nuclear processing industry. Specifically, in the last few years, three new SGS models have been created: a stand-alone unit with variable geometry to assay sealed containers under the direction of an operator who loads and unloads the samples, an SGS capable of assaying samples within a glovebox containing corrosive fumes, and an SGS for waste measurements within glovebox containment. Software is continually improved to automate the assay, to provide measurement control, and to provide flexibility for future assay needs.

II. VARIABLE-GEOMETRY SGS

A. Mechanical Design

This stand-alone model is housed in a sheet metal cabinet with interlocked doors for insertion and removal of assay items by the operator. The machinery can only operate if the doors are closed for the protection of the operator. This SGS has two tables, one to support the germanium detector and its integral collimator and shield, and another to support a shadow shield, transmission source assembly, and a shutter assembly. The tables ride on ball-bushing rails and are driven from a single shaft with right- and left-handed threads, one thread for each table. This allows the tables to come either closer together or farther apart depending on the sense of rotation of the shaft, which is driven by a translation motor in the horizontal direction. The elevation and rotation mechanism, which causes the sample to be scanned across the angle of view of the detector collimator, is mounted between the rails and between the translation tables.

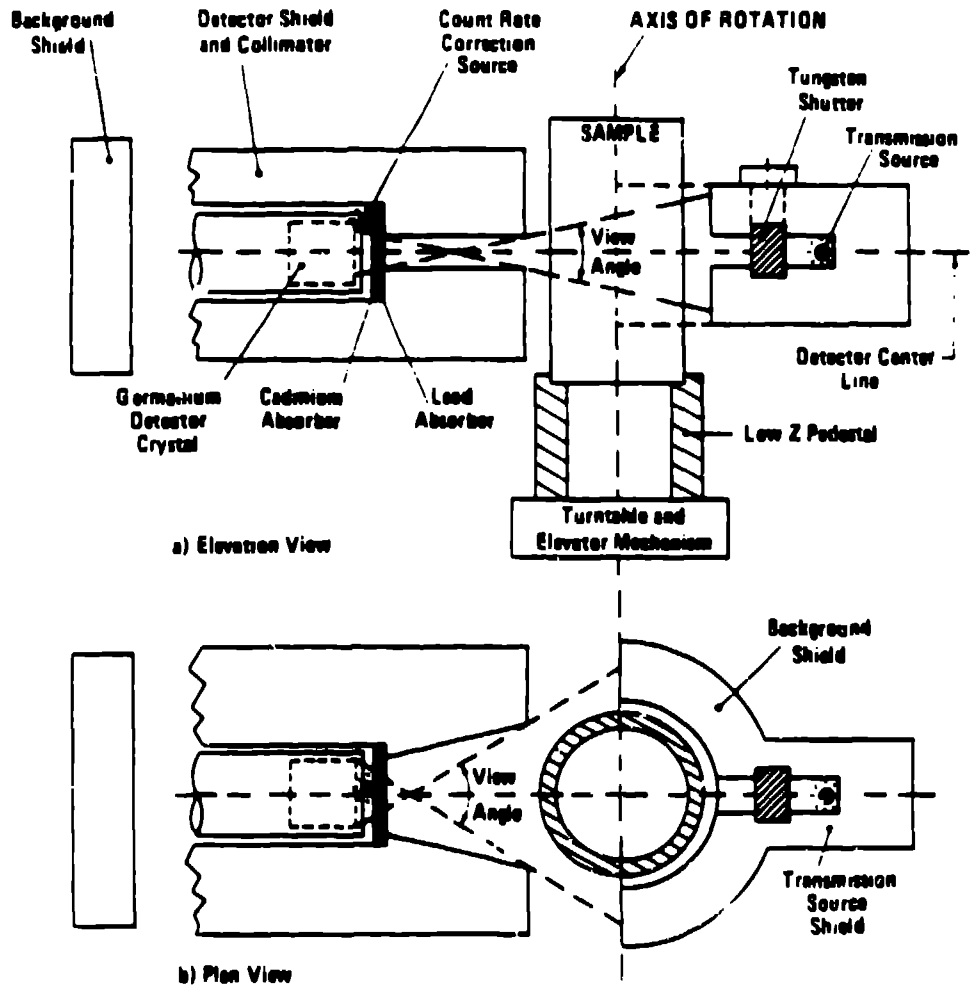

Fig. 1. General arrangement for segmented gamma-ray scanning.

1. Detector Collimator and Shield Assembly. An integral design to shield the detector and provide the collimator slit for viewing the sample was created as two identical shield halves, each containing a hemicylindrical opening for the detector cryostat and corresponding halves of the collimator slit. Such a design allows for easy fabrication using a stainless steel outer skin into which lead can be cast. Machined tungsten inserts for the collimator could be used to eliminate x rays with energies produced by fluorescence of lead. Pairs of inserts with different slit heights could be used for assay campaigns among samples with greatly varying height. However, the design for this model as well as for the other two to be described within calls for a single slit height of 12.7 mm and a collimator depth (horizontal extent) of 101.6 mm, for an aspect ratio of 8:1.

2. Detector Table. The detector Dewar and the collimator and shield are supported by separate shelves on a common table. The split design of the collimator and shield allows for easy installation or removal of the coaxial germanium detector mounted in its 30 l Dewar. A horizontal dipstick cryostat model is used. The table is supported by four ball bushings riding as pairs on the two supporting rails. A block tapped with a left-handed thread is mounted to the base plate of the table. The drive shaft for translation passes through this nut.

3. Shadow Shield. This shield is easily fabricated as a stainless steel weldment into which lead can be cast. It has a hemicylindrical shape and is supported concentric to the axis of rotation of the sample when the translating tables are as far apart as [illegible]

This shield prevents the detector from receiving gamma rays through the collimator from sources beyond the sample.

4. __Shutter__. The shadow shield is machined to house a shutter assembly that consists of a tungsten shutter with a 12.7-mm hole, a housing for the sliding tungsten block, and a solenoid assembly to actuate the movement of the tungsten shutter. The actuation is in a vertical direction. The shutter opens when the solenoid is energized and closes when the solenoid voltage goes to zero. The shutter is positioned between the sample and the transmission source. When open, the hole in the shutter is concentric with the detector crystal. The axis of the hole is perpendicular to the axis of rotation of the sample.

5. __Transmission-Source Assembly__. The transmission-source assembly can be a single-source plug mounted into the shadow shield or a wheel containing several sources, which can rotate to place one source at a time into position behind the shutter. The plug or wheel has been designed to be machined from tungsten. The wheel design includes a Geneva mechanism driven by a small stepping motor to provide reproducible positioning of up to eight sources. The wheel allows for automatic assays with multiple sources for multiple assay isotopes within the same sample.

6. __Shadow-Shield Table__. This is a single-shelf table also supported by four ball bushings riding on the same two rails as the detector table. It has a right-handed nut mounted to it for the translation screw. The shadow shield, shutter assembly, and transmission-source assembly are mounted to the table so that the source and open-shutter hole are concentric with the detector crystal.

7. __Elevation and Rotation Mechanism__. The elevator drives the sample-rotation table up and down. Three ball-bushing rods guide the movement and three ball-nut screws driven by a timing belt common to a stepping motor provide the vertical motion. The sample-rotation table is driven directly by another stepping motor mounted beneath it. The table has concentric indentations that match the cylindrical pedestals used to support the cylindrical sample containers. The pedestals have plastic walls to provide minimal attenuation when the detector views the region just beneath a sample can. The elevator is designed to have sufficient travel so that one can overscan the sample, that is, measure two or three segments both above and below the sample to be confident that all nuclear material was viewed with equal efficiency.

B. Electrical Design

The instrument is computer controlled. Therefore, the moving components generally require electric motors or the solenoid in the case of the shutter. Sensors are also required to prove that movements requested are indeed completed. Mechanical limit switches are also used to prevent damage if a motor continues to run beyond the usual sensor position. The instrument computer is master to a slave microprocessor that controls mechanism movements. Data acquisition proceeds between the computer and a dedicated multichannel analyzer (MCA) that collects the digitized pulses from conventional gamma-ray spectroscopy system components.

1. __Drive Motors__. Stepping motors can be used for the elevator, rotator, translator, and source wheel. An alternating-current reversible motor has also been used for the translator. Stepping motors, drivers, and indexers containing microprocessors can be obtained commercially. Special drive circuits have also been used. An encoded elevator motor is desirable to insure equal steps during the segmented assay.

2. __Position Sensors__. Proximity switches have been used to indicate the lowest elevator position, the highest elevator position with the tables far apart, the highest allowed elevator position with the tables close together, the far-geometry position of the tables, the near-geometry position of the tables, the rotation of the turntable, and the open or closed condition of the doors. Optical switches have been used in conjunction with a disc with unique patterns of holes to inform the computer as to which of the eight source-wheel positions is in place behind the shutter. The disc is mounted to the shaft between the source wheel and the Geneva star wheel.

3. __Mechanical Limit Switches__. Mechanical microswitches are used to prevent the elevator motor from driving the elevator into any mechanical stops, either near the top or bottom of travel. The limit switches are set just beyond the usual stopping positions signaled to the computer by the position sensors. If a position sensor fails, or the computer fails, the limit switch will disable the rotation of the elevator motor independent of the computer.

4. __Microprocessor Control__. Commercial indexers and controllers designed at Los Alamos have been used to monitor the sensors and control the motors. Los Alamos-produced software resident in the microprocessor is operated under command of an instrument computer to provide the automated assays desired. Typically, the microprocessor performs the sequenced movements and checks for unsafe conditions, for example, sensors reading incorrectly. The instrument computer checks the status of the hardware as determined by the microprocessor and proceeds to the next step or halts the assay with an error message to the operator's terminal.

5. Data Acquisition and Analysis. The instrument computer is interfaced to the MCA. The MCA collects the gamma-ray spectra under command of the computer. The germanium detector preamplifier output is shaped and amplified by a nuclear instrumentation module (NIM) spectroscopy amplifier. The amplifier output is digitized by a NIM analog-to-digital convertor (ADC). The digitized data are stored in the MCA under the control of a digital stabilizer, also a NIM unit. Zero stabilization is based on a low-energy peak, a gamma ray from a low-activity source affixed to the detector cryostat. The rate of gamma rays in this low-energy peak is used by the analysis software to correct for electronic losses resulting from deadtime and pileup. This source is indicated in Fig. 1 as the count rate correction source. Gain stabilization is usually based on a gamma ray from the transmission source having an energy near the top end of the ADC range.

The assay sequence follows an initial dialog between the operator and the instrument computer using the operator's terminal. The near or far geometry is then set, and the elevator positions the turntable at the appropriate upper sensor. The operator is requested to load the sample and its pedestal, to close the door, and to press the return key on the terminal when ready. The elevator moves to the preset position for the first segment. The turntable is rotated and the MCA collects data for a preset time interval. Data are transferred to the computer for analysis and the elevator moves to the next segment. At each segment, data are collected with the transmission source shutter open (called single-pass assay) or with both the shutter open and closed (called double-pass assay) as per instructions by the operator in the initial dialog. After completion of the final segment data collection, the turntable is turned off and the elevator returns the turntable to its upper sensor position. The operator is then instructed to open the door, remove the sample and its pedestal, and press the return key on the terminal when ready. The computer then will cue the operator for the dialog for the next assay.

The analysis includes computation of a corrected count rate for every gamma ray requested among those emitted by the radioactive isotopes in the sample. This is done at each segment. The sums over all segments of these rates, gamma ray by gamma ray, provide the total corrected rates that are proportional to the masses of the isotopes emitting the gamma rays. The corrected count rate for a single gamma ray is the product of the observed rate (photopeak area divided by the time to collect it), the correction factor for rate related losses resulting from deadtime and pileup, and the correction factor for attenuation by the container and the material within the container. The attenuation correction factor is a function of the transmission for the gamma-ray energy being determined. This transmission is inferred from measured transmissions of gamma rays from the transmission source.

Traditionally, software has been written for the assay of a single isotope using one of its gamma rays and one or two gamma rays from a single transmission source. With the advent of powerful microcomputers, Los Alamos is now producing SGS code, which allows a supervisory operator to define several gamma rays from several assay isotopes along with similar numbers of gamma rays from one or more transmission sources. A transmission source wheel is required for automatic assay with more than one transmission source. The software will produce a total corrected count rate for each of the assay gamma rays. The appropriate transmission for attenuation correction at a given energy is obtained through use of a general interpolation algorithm based on the linear relationship between the logarithm of the energy and the logarithm of the attenuation coefficient. Transmission-source gamma rays near the assay gamma ray of interest are used in the interpolation or nearby extrapolation. Appropriate standard reference materials must be used to establish the calibration constants--one per assay gamma ray. An appropriate standard could contain a uniform mixture of fine nuclear material dispersed among fine particles of a diluting matrix. The calibration constant is the total corrected count rate divided by the mass of the isotope in the standard sample emitting the gamma ray.

Assays of unknown samples using multiple gamma rays can be used to identify items containing large particles of nuclear material, which will absorb more of their own emitted radiation at lower energies than at higher energies. A companion paper, "Recent Advances in Segmented Gamma Scanner Analysis," will discuss current approaches to correct for self-absorption using multiple gamma rays from an emitting isotope.

6. Performance. In an implementation of the variable-geometry SGS for assay of highly enriched uranium with ^{169}Yb as the transmission source, five standard reference materials were produced with isotopic ^{235}U masses of 15, 35, 155, 225, and 300 g, respectively. Ninety six assays of these standards were performed in the near geometry to test the SGS: 18, 27, 15, [illegible], and 18 each, respectively. The attenuation correction factor varied from 1.6 at 15 g to [illegible] at 300 g, a range of 231%. The relative sample standard deviation of the calibration constant, the total corrected count rate per gram of ^{235}U, over the sample of 96 assays was [illegible]%. The estimated precision of any single assay in the sample varied from 0.37 to 0.87% relative standard deviation, depending on the item. These data show a lack of bias for this set of [illegible]ly prepared standard reference [illegible]

The SGS technique is accurate provided the nuclear particles are not too self-absorbing.

III. IN-LINE SGS FOR A GLOVEBOX WITH A CORROSIVE ATMOSPHERE

To facilitate assay of scrap in the aqueous processing section of the Los Alamos Plutonium Facility, an SGS was developed to assay stainless steel cans of scrap within the glovebox containment. The atmosphere within the glovebox is usually acidic; therefore, this unit provides a minimum number of moving parts within the corrosive environment of the glovebox. A cylindrical well is suspended from the bottom of the glovebox. The well surrounds a turntable that is mounted through a bearing to a bar magnet beneath the bearing. The bar magnet is suspended just above the bottom of the well. Beneath the well is another bar magnet attached to a direct-current motor through another bearing assembly. The two magnets couple through the nonferromagnetic stainless steel of the bottom of the well to allow rotation of the sample can upon the turntable. The elevator drives the entire detector, collimator, shielding, shutter, and transmission source assembly to scan the sample within the well. The elevator is driven with a stepping motor and a timing belt and ball-nut screw mechanism similar to that previously described. The detector and Dewar are about 170 mm shorter than the standard 30-l Dewar models commercially produced, which is a drawback in the event the detector fails. To partially compensate for this possibility, an N-type detector with higher neutron damage threshold was chosen. A neutron-damage repairable cryostat was also specified. The unit has a collimator and shield assembly, shadow shield, shutter, and transmission-source plug similar to those previously discussed. The plug houses a single ^{75}Se source. The assay software is restricted to ^{239}Pu assay at 345 and 414 keV.

IV. IN-LINE SGS FOR WASTE CERTIFICATION

All waste to be stored at the Waste Isolation Pilot Plant (WIPP) of the United States Department of Energy, located at Carlsbad, New Mexico, must be certified according to the rules for acceptance at WIPP. The Los Alamos Plutonium Facility waste management team has commissioned the Safeguards Assay Group to provide an in-line SGS and an in-line neutron coincidence counter for assay of containers up to 210-mm diam by 406-mm tall. The two instruments will be controlled by the same computer. Because the SGS tends to assay low when large particles are present and the neutron counter tends to assay high when unknown induced fission occurs, the pair of results for each item should put a bound on the assay value of the waste item. It is hoped that, as the instruments are used, segregated wastes will be characterized to quantify and correct biases. The contents of about 20 of the largest cans used in these instruments can be "bagged" out into a 208-l drum for shipment to WIPP. The sum of the assays of the cans making up the contents of the drum should be more accurate than an assay of the drum alone. The assay value will be declared as the sum. A confirmatory measurement of the 208-l drum will probably be made for assurance.

The in-line SGS for waste certification, commonly called the WIPP SGS, features good segmentation of the large can, complete detector and shadow shielding, shutter, and transmission-source wheel assemblies similar to those previously discussed. However, its elevator and rotator assembly is housed within the glovebox containment in a deep well beneath the glovebox. The neutron coincidence counter is wrapped around another well beneath the same glovebox. This instrument glovebox has a dry atmosphere free of acidic corrosive fumes. Therefore, the small stepping motors for the elevator and rotator are expected to perform well for a long period of time. The elevator is another ball-bushing rod and ball-nut screw assembly, but is driven with stainless steel sprockets and chains by the encoded elevation stepping motor. The rotation stepping motor is directly coupled to the turntable, which is fabricated as a thin-walled stainless steel pedestal. The elevator and rotator assembly can be hoisted up into the glovebox if maintenance is required. A single multiple-pin vacuum feedthrough in the glovebox wall provides the electrical pathways for control of the stepping motors and monitoring of the elevation and rotation sensors. The mechanism is entirely stainless steel with the exception of the stepping motors, proximity sensors, and mechanical microswitches. A feature of the well is the inclusion of a bolt-on reentrant rectangular box into which the collimator assembly slips so as to give a minimal gap between the collimator and the wall of the sample can for improved segmentation and sensitivity. The region of the box through which the gamma rays penetrate on their way to the collimator is thinner than the rest of the glovebox walls to minimize attenuation. The detector and its shield and collimator are supported by a table supported with adjustable jacks from the floor. The shadow shield, shutter, and transmission source wheel assembly are supported by a second free-standing table on the opposite side of the well. Software in process will be nearly identical to that for the variable-geometry SGS, four e-wheel model.

V. CONCLUSION

The three new versions of the SGS provide rugged, highly automated, and accurate tools for assay of low-density scrap and waste, which are still important material categories in the accountability realm of safeguards in the nuclear industry. They were designed with careful attention to the physics required by the SGS technique and engineered for reliable and safe operation. The use of integral shielding makes them nearly immune to background radiation. Good segmentation without much loss of sensitivity makes them useful with heterogeneous distributions within a sample container. The addition of the source wheel and the more general software makes them expandable to assay of additional isotopes in the future.